SAND2020-2292C

True Series Resonance Oscillator using Active Shunt Capacitance Cancellation

Darren W. Branch
Biological and Chemical Sensors Department
Sandia National Laboratories
PO Box 5800, MS-1425
Albuquerque, NM 87185
dwbranc@sandia.gov

Kurt O. Wessendorf
Magnetic and Frequency Devices Department
Sandia National Laboratories
PO Box 5800, MS-0525
Albuquerque, NM 87185

***Abstract*—A true series resonance oscillator has been developed for use with a wide-range of 1-port resonance-based sensors and devices. The oscillator effectively removes the shunt capacitance C_o, allowing the true series resonance to be monitored, providing the optimum sensitivity across a wide range of frequencies (i.e. kilohertz to gigahertz), shunt capacitances, and quality factors (Q) for the first time. It is well-known that non-zero shunt capacitance alters the impedance by shifting the location of the impedance minimum and the zero-phase crossing while causing significant impedance distortion. We have developed an active shunt capacitance cancelling oscillator (ASSCO) that removes any shunt capacitance across the resonator by supplying the circuit an equal "dummy" capacitance from a cancelling current. The oscillator does not require automatic gain control (AGC) and the resonator can be grounded to reduce parasitic contributions.**

Keywords—oscillator, sensors, MEMS, piezoelectric, microresonator

I. INTRODUCTION

Monitoring the series resonant frequency and damping of resonators across a broad range of frequencies and Q's is paramount for reliable sensing and monitoring applications. Most notably, the quartz crystal microbalance (QCM) has been widely leveraged for film-thickness monitoring, gravimetric chemical and biological sensing, temperature, and fluid monitoring. As a result, there are numerous monitoring methods for the QCM such as impedance, oscillators, and ring-down [1]. However, monitoring the series resonant frequency applies to other sensors such as microelectromechanical systems (MEMS), piezoelectric, ceramic, coaxial, and dielectric based resonators. Applications include RF/microwave components, temperature monitoring [2], chemical and biological detection [3-5], and measuring liquid properties [6]. Although oscillator approaches vary widely, common characteristics include loop amplifiers (G) to overcome feedback losses, gain limiting or compression, gain or phase adjustment, and feedback-loop sampling [1]. Ideally, the circuits oscillation frequency should coincide with the series resonant frequency. Thus, efforts have been made to cancel the resonators shunt capacitance while keeping the motional amplitude at a constant level. Methods include automatic gain control [7], phase-locked loop (PLL) [8], and more recently a PLL with a differential amplifier [9]. However, previous approaches lack two key capabilities: operational bandwidth for high-frequency resonators and the ability to electrically ground the resonator, and thus suffer from perturbations and severe parasitic contributions that limit current applications.

This work is supported by Sandia National Laboratories Laboratory Directed Research and Development. Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525. The views expressed in the article do not necessarily represent the views of the U.S. Department of Energy or the United States Government.

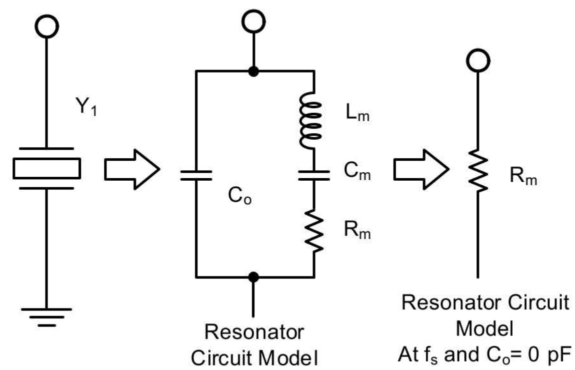


Fig. 1. Equivalent circuit of a 1-port resonator with an impedance load. When $C_o = 0$, the series resonance occurs exactly where the phase crosses zero at the minimum impedance or series resonance. This is because the resonance is now due to the combination of L_m - C_m where Y_1 appears as R_m.

II. IMPACT OF SHUNT CAPACITANCE

The equivalent circuit of a 1-port acoustic resonator (Y_1) is shown in Fig. 1. C_o is the shunt capacitance, R_m is the motional resistance (R_m), L_m is the motional inductance, and C_m is the motional capacitance. The motional arm of the resonator is due to contributions from the electromechanical or piezoelectric characteristics of the resonator. If C_o is removed, the circuit reduces to R_m at the series resonant frequency. For an unloaded piezoelectric resonator, the admittance is given as:

$$Y_u = j\omega\left(C_o + C_p\right) + \frac{1}{R_m + j\omega L_m + \frac{1}{j\omega C_m}} \quad (1)$$

where C_p is a parasitic capacitance that can be removed by de-embedding. The motional capacitance is related to the resonator shunt capacitance as:

$$C_m = \frac{8k_t^2 C_0}{N^2\pi^2} \quad (2)$$

where k_t^2 is the electromechanical coupling of the resonator and N is the mode. Likewise, the motional inductance is related to the motional capacitance as:

$$L_m = \frac{1}{4C_m f_s^2 \pi^2} \quad (3)$$

Additional surface loading of the one-port resonator can be modeled by adding impedance (Z_L) to the series arm shown in Fig. 1. Using (1), the one-port impedance ($Z = Y^{-1}$) was computed for the ideal case when $C_o = 0$ and for $C_o = 4$pF as shown in Fig. 2. Non-zero shunt capacitance alters the impedance by shifting the location of the minimum and the zero-phase crossing while causing significant distortion. In some cases, a zero-phase crossing may not exist. The distortion for non-zero shunt capacitance becomes increasingly worse as the resonator loss increases (i.e. low Q) and at higher frequencies. The shunt capacitance C_o is always a non-zero value, due to the electrodes and the additional capacitance of the associated fixture or circuit substrate used for the sensor. To obtain the true f_s and resonator loss it is highly desirable remove the shunt capacitance because more useful information can be generated by an oscillator or other measurement equipment. When $C_o = 0$, the series resonance occurs exactly where the phase crosses zero at the minimum impedance or series resonance. This is because the resonance is now due to the combination of L_m - C_m where Y_1 appears as R_m at the series resonance (f_s). The series resonant frequency is where there is the highest sensitivity to operational changes (e.g. surface binding or temperature). Resonator-sensor applications require monitoring f_s and R_m as this provides information relating to mass change (Δ_m) and viscosity-density of the measured sample, (R_m or Q). It is important to note that the location of f_s for $C_o = 0$ may differ from the location of the quality factor (Q) due to the phase shift contribution from C_o:

$$Q_s = \frac{f_s}{2}\frac{d\angle Z_{11}}{df}\bigg|_{f=f_s} \equiv \frac{2\pi f_s L_m}{R_m} \quad (4)$$

where Z_{11} is the 1-port impedance and f_s is the series resonant frequency. Equivalently, Q can be computed from L_m and R_m.

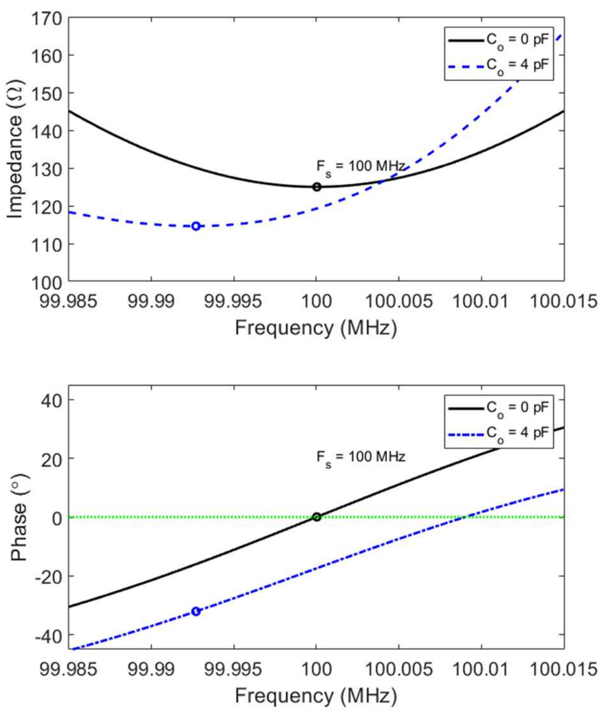


Fig. 2. Impact of shunt capacitance C_o on the resonator. When is $C_o = 0$ pF, the impedance is a minimum where the phase crosses through zero at f_s. Non-zero shunt capacitance ($C_o = 4$ pF) alters the impedance by shifting the location of the minimum and the zero-phase crossing. $C_m = 6.4$ fF, $R_m = 125\ \Omega$, and $L_m = 390\ \mu$H.

III. Active Shunt Capacitance Cancelling Oscillator (ASCCO)

An oscillator circuit was developed to remove the impedance contribution of the shunt capacitance C_o, allowing the non-electrical (e.g. acoustic) contributions to be measured by the oscillator. This method is called Active Shunt Capacitance Cancelling Oscillator (ASCCO) as shown in Fig. 3. The oscillator tracks the true series resonant frequency (f_s) and thus provides the best sensitivity to perturbations such as temperature, mass, and viscosity · density product, which are critical for sensor applications. When C_o is removed a series resonant oscillator circuit is formed that "servos" the zero-phase point of this effective resonator impedance, which is determined by the motional arm of the resonator structure. The zero-impedance phase of this motional arm occurs at the f_s of the resonator, where the shunt capacitance complicates finding the "true" f_s of a resonator since this frequency depends on this shunt capacitance and the resonator loss, R_m. When the shunt capacitance at series resonance is removed, the resonator impedance simplifies to R_m (Fig. 1). This does not require deconvolving the shunt capacitance. The active shunt capacitance cancelling oscillator allows the above conditions by removing any shunt capacitance across the resonator by supplying the circuit an equal "dummy" capacitance that generates a cancelling current used in the oscillator to remove

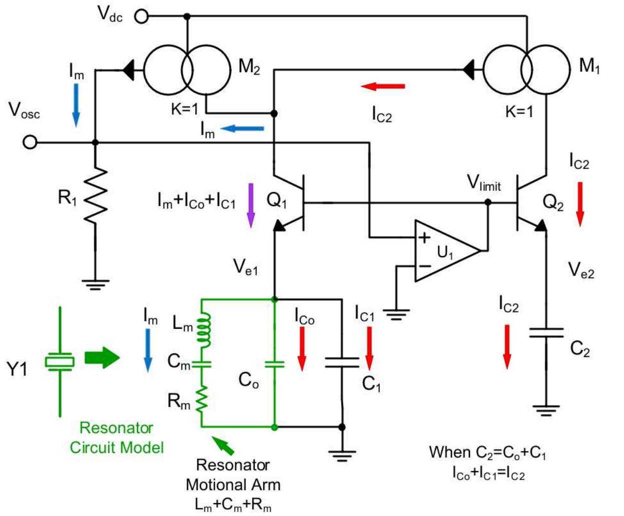


Fig. 3. The Active Shunt Capacitance Cancelling Oscillator (ASCCO) removes the effects of the shunt capacitance C_o. The current mirror M_1 passes on a copy of the dummy capacitance to mirror M_2 where the summing of the two current legs Q_1 and Q_2 cancel the shunt capacitance currents leaving only the motional arm current.

electronically the non-desired resonator shunt capacitance. This circuit also supplies the means to output a dc voltage proportional to the amplitude of oscillation which is also proportional to resonator loss, R_m. At the series resonance (f_s) of L_m - C_m, only R_m remains and $C_o = 0$ or C_o is a very large reactance compared to R_m.

The oscillator uses the emitters of Q_1 and Q_2 as active ports to convert impedances of the resonator with shunt capacitance C_1 (emitter of Q_1) and a dummy capacitance, C_2 (emitter of Q_2) into currents that will be summed at an output node such that the equivalent circuit functions as an oscillator where the frequency of oscillation only depends only the motional arm of the resonator circuit. This is true when the output impedance of Q_1 and Q_2 are less than the impedances at these nodes, or the transistors are operating as excellent voltage followers, which means the emitter voltages, V_{e1} and V_{e2} are very close to the output voltage of the limiting amplifier U_1. The limiting amplifier in this case is a non-inverting amplifier with gain (GU_1) of approximately 2.25 and the output is fixed to limit to an amplitude a predetermined voltage, in this case approx. 0.4 Vp-p. This voltage is independent of the input amplitude (V_{osc}) after this level is reached. To cancel the effects of the shunt capacitance across the resonator $C_o + C_1$ the value of C_2 (dummy capacitor) needs to equal $C_o + C_1$. As shown in Fig 3, the mirror M_1 passes on a copy of the dummy capacitance current to mirror M_2 where the summing of the two current legs Q_1 and Q_2 cancel the shunt capacitance currents leaving only the motional arm current. Current I_m generates an output voltage V_{osc} at node R_1. The resistance R_1 is real, and equal to 340 Ω, the gain of U_1 is also real so the loop gain A_v is: $A_v = R_1(GU_1)/(XL_m + XC_m + R_m)$. Where XL_m and XC_m are the reactance of L_m and C_m, respectively. The circuit will oscillate when the loop gain is greater than one and the oscillation frequency occurs where the loop function is real, or 2π radians. This condition only occurs when $XC_m + XL_m = 0$ or when: $F_{osc}=1/(2\pi\sqrt{(L_mC_m)})$. The loop gain equation at this frequency is $R_1(GU_1)/R_m$. The voltage at node V_{osc} is simply the limiting voltage of U_1 (0.4Vp-p) multiplied by the ratio (R_1/R_m). In effect the resistor R_1, which can be relatively large, is shunted with capacitance. Thus, in practice the node V_{osc}, R_1 uses a parallel tank circuit to allow a wide possible range of operational frequencies and selection of a resonator overtone operation if desired.

In Fig. 4, a simplified version of the active capacitance canceling oscillator in shown. The output tank, at V_{osc} is a parallel tank circuit where R_1, L_t - C_t is a relatively low Q parallel tank circuit where L_t is chosen resonant with C_t at the desired resonator frequency. At this frequency the tank impedance is simply R_1 and the previous equations and theory apply. The amplitude of the oscillation is taken from a node inside U_1, which provides a half wave rectification of the node V_{osc}. This signal ranges from a low to high-level sinewave depending on the resonator loss and other parameters. The rectified waveform is buffered and filtered to provide a dc voltage proportional to the amplitude of the oscillation voltage at V_{osc}. The oscillator will operate with a series resistance from 10 Ω to 2kΩ. Above this value, the oscillate may fail to operate because of decrease in the overall loop gain of the detection circuit.

IV. ASCCO OPERATION USING SH-LSAW RESONATOR

To demonstrate the efficacy of the ASCCO approach, piezoelectric resonators were fabricated to operate at 100 MHz. The acoustic resonators leveraged the propagation of shear-horizontal leaky surface acoustic waves (SH-LSAW) [10]. To minimize resistive losses when using the ASCCO circuit, the series resistance of the resonator was designed to be ~50 Ω. If the motional resistance is too low (i.e. < 10 Ω), the sensor appears as an electrical short to the monitoring circuit, which prevents start-up of the oscillator. In this case, impedance matching is required when the series resistance is less than 10 Ω. If the series resistance exceeds > 2kΩ, the loop gain of the detection will be too high and cause excessive noise. The interdigital transducers (IDTs) were fabricated using 5000Å tungsten (W) with a 100 Å Ti adhesion film to provide high acoustic reflectivity per finger pair. The wavelength of the ST-90°X rotated resonators were 46 μm,

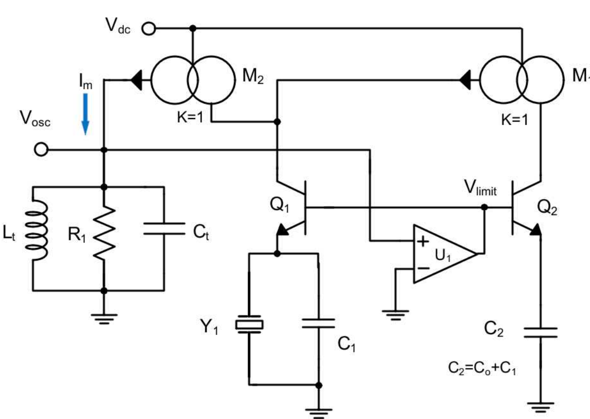
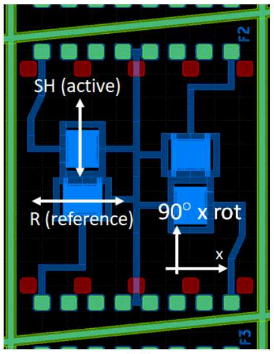
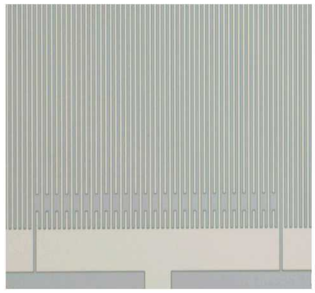


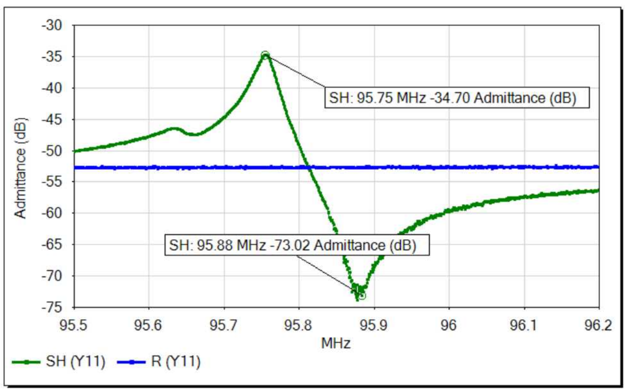
Fig. 4. Simplified oscillator circuit with active shunt C_o removal.



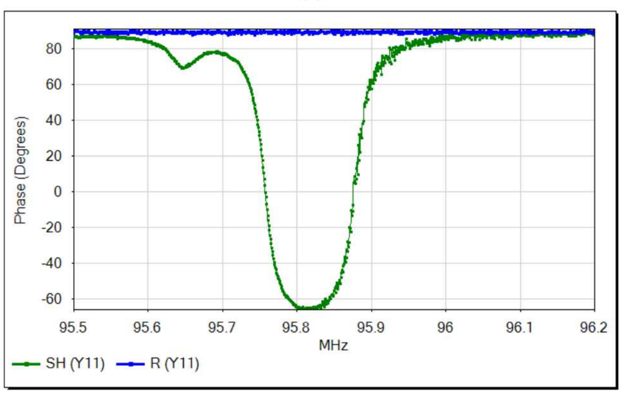
(a)



(b)



(c)



(d)

Fig. 5. SH-LSAW resonator fabricated using thick tungsten (W) electrodes, **a)** The active sensor is vertical direction, propagating the SH-LSAW mode, **b)** a single SH-LSAW resonator, **c)** measured admittance (SH mode) and reference (R) and **d)** phase (SH node) and reference (R) showing the $j\omega C_o$ contribution. The resonators measured 1.8 mm x 2.4 mm.

giving a resonator frequency of ~100MHz. The finger width was 11.5 µm with an aperture of 25λ and 25 finger pairs. The sensors had 10 nm of SiO_2 deposited to passivate the IDTs. In Fig. 5a and b, the SH-LSAW resonator is shown with a piezoelectric or active sensor propagating in the vertical direction and an inactive reference sensor (R) propagating along the x-axis. The reference sensor had a shunt capacitance indistinguishable from the active sensor and served as a reference shunt capacitor (R) on the same die. The purpose of the inactive channel is to remove of the effect of the non-zero shunt capacitance (C_o) in parallel with the motional resistance (R_m), motional inductance (L_m), and motional capacitance (C_m) of the sensor. For other sensors such as FBAR or MEMS resonators, the reference shunt capacitor could be fabricated alongside the resonator to match the capacitance of the resonator.

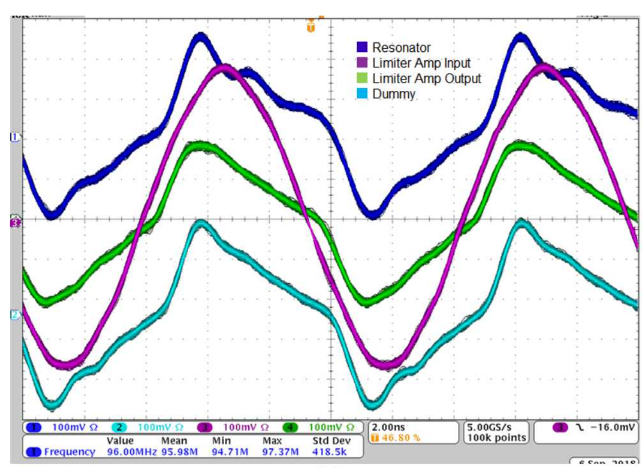
We demonstrated the oscillator using ST-90° rotated X-cut quartz resonators, where the active port had f_s = 96 MHz and the reference was a weakly coupled Rayleigh SAW that was out-of-band compared to the SH-LSAW mode due to the orthogonal propagation direction (Fig 5). The series resonant frequency was slightly lower than the intended design of 100 MHz due to the heavy metal loading of the tungsten electrodes. The admittance and phase in shown in Fig. 5c and d for the piezoelectrically active sensor and inactive reference device. The trace for R(Y11) in Fig. 5c shows that reference appears as a capacitance with the $j\omega C_o$ contribution. In Fig. 6, we show the oscillator output at 96 MHz, where it can operate with series resistances ranging from 10 Ω to 2 kΩ.

V. Single-Port Resonator Capacitance Canceling Verification

To confirm the ASCCO circuit removed the shunt capacitance and tracked the true series resonance, capacitance was added to the active and dummy oscillator ports in sequence. Adding a 2.5 pF capacitor to the active resonator port caused an equal but opposite frequency shift +30 ppm. Adding a 2.5 pF capacitor to the dummy or reference resonator port caused an equal but opposite frequency shift of -49 ppm. Both ports had an expected but small decrease in amplitude. Adding equivalent capacitors to both oscillator ports resulted in a negligible shift in the oscillator frequency of 2 ppm and the oscillator amplitude remained unchanged. This showed the ASSCO circuit is tracking the true series resonance frequency.

VI. Conclusions

In this work, an active shunt capacitance cancelling oscillator (ASCCO) was developed for a wide range of



(c)

Fig. 6. Oscilloscope measurements of the ASCCO circuit showing the resonator, limiter amplifier input and output, and dummy oscillator sections.

resonator devices. The method can monitor the true acoustic series resonant frequency and damping of the resonator, providing the optimum sensitivity across a wide range of frequencies (i.e. kilohertz to gigahertz), shunt capacitances, and quality factors (Q) for the first time. Since the ASCCO avoids impedance distortion and phase shift problems associated with non-zero shunt capacitance, it is valuable for sensor applications. Though we demonstrate the method using SAW resonators, it is applicable to other piezoelectric resonators such as FBAR, BAW, Lamb, contour-mode as well as cantilever, MEMS, and ceramic resonators.

ACKNOWLEDGMENT

The authors are grateful to Joe Bischoff and Lidia Ruiz for their contributions to this work. These devices were fabricated in the Sandia MESAFab and the authors thank the MESAFab operations team for fabrication contributions.

REFERENCES

[1] A. Alassi, M. Benammar, and D. Brett, "Quartz Crystal Microbalance Electronic Interfacing Systems: A Review," *Sensors,* vol. 17, no. 12, pp. 1-41, 2017.

[2] F. T. Goericke, M. W. Chan, G. Vigevani, I. Izyumin, B. E. Boser, and A. P. Pisano, "High temperature compatible aluminum nitride resonating strain sensor," presented at the 16th Intern. Solid-State Sensors, Actuators and Microsystems Conference, Beijing, China, 2011.

[3] W. Pang, H. Zhao, E. S. Kim, H. Zhang, H. Yuc, and X. Hua, "Piezoelectric microelectromechanical resonant sensors for chemical and biological detection," *Lab on a Chip,* vol. 12, pp. 29-44, 2012.

[4] J. Lu, L. Zhang, H. Takagi, T. Itoh, and R. Maeda, "Hybrid Piezoelectric MEMS Resonators for Application in Bio-Chemical Sensing," *J. Appl. Sci. and Engin.,* vol. 17, no. 1, pp. 17-24, 2014.

[5] D. Chen, Z. Zhang, J. Ma, and W. Wang, "ZnO Film Bulk Acoustic Resonator for the Kinetics Study of Human Blood Coagulation," *Sensors,* vol. 17, no. 5, May 3 2017.

[6] L. Qin, Q. Chen, H. Cheng, Q. Chen, J.-F. Li, and Q.-M. Wang, "Viscosity sensor using ZnO and AlN thin film bulk acoustic resonators with tilted polar c-axis orientations," *J. Appl. Phys.,* vol. 110, pp. 1-11, 2011.

[7] C. Chagnard, P. Gilbert, A. N. Watkins, T. Beeler, and D. W. Paul, "An electronic oscillator with automatic gain control: EQCM applications," *Sensors Actuators B,* vol. 32, pp. 129-136, 1995.

[8] V. Ferrari, D. Marioli, and A. Taroni, "Improving the accuracy and operating range of quartz microbalance sensors by a purposely designed oscillator circuit," *IEEE Trans. Instrumen. Meas.,* vol. 50, pp. 1119-1122, 2001.

[9] J. Toledo *et al.*, "Piezoelectric resonators and oscillator circuit based on higher-order out-of-plane modes for density-viscosity measurements of liquids," *J. Micromechan. Microeng.,* vol. 26, p. 084012, 2016.

[10] M. Kadota, T. Yoneda, K.Fujimoto, T. Nakao, and E. Takata, "Resonator Filters Using Shear Horizontal-Type Leaky Surface Acoustic Wave Consisting of Heavy-Metal Electrode and Quartz Substrate," *IEEE Trans. Ultrason., Ferroelectr., Freq. Contr.,* vol. 51, no. 2, pp. 202-210, 2004.